

# Charmonium Spectroscopy Below Open Flavor Threshold

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Latest experimental results in the charmonium spectroscopy below  $D\bar{D}$  breakup threshold are reviewed.

## 1. Introduction

Charm quark has large mass ( $\sim 1.5$  GeV) compared to the masses of  $u$ ,  $d$ ,  $s$  quarks. Velocity of the charm quarks in hadrons is not too relativistic ( $(v/c)^2 \sim 0.2$ ). Strong coupling constant  $\alpha_s(m_c)$  is small ( $\sim 0.3$ ). Therefore charmonium spectroscopy is a good testing ground for the theories of strong interactions: quantum chromodynamics (QCD) in both perturbative and nonperturbative regimes, QCD inspired purely phenomenological potential models, nonrelativistic QCD (NRQCD) and lattice QCD.

There are 8 bound states of charmonium below the  $D\bar{D}$  breakup threshold (Fig. 1). These are spin triplets  $J/\psi(1^3S_1)$ ,  $\psi(2S)(2^3S_1)$ ,  $\chi_{c0,1,2}(1^3P_{0,1,2})$  and spin singlets  $\eta_c(1^1S_0)$ ,  $\eta_c(2S)(2^1S_0)$ ,  $h_c(1^1P_1)$ . Only  $J/\psi$  and  $\psi(2S)$  can be produced directly in  $e^+e^-$  annihilation. A lot is known about these triplet states. Spin singlet states population via radiative transitions from the vector states is either very weak (M1 transitions for  $\eta_c(1S)$ ,  $\eta_c(2S)$ ), or  $C$ -forbidden ( $h_c(1^1P_1)$ ). Accordingly, little is known about these singlet states.

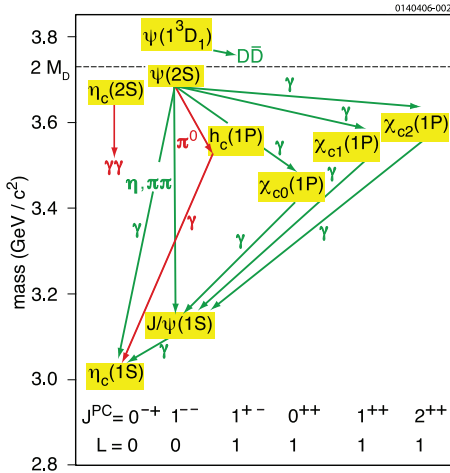


Figure 1: Spectra of the states of charmonium below  $D\bar{D}$  breakup threshold.

The status of charmonium states below  $D\bar{D}$  breakup threshold is summarized in Table I. The masses and widths from PDG 2007, as well as a number of measured decay channels from PDG 2002, 2004 and 2007 are presented separately for *spin-triplet* and *spin-singlet* states.

Table I Status of charmonium states.

	Mass (MeV) PDG 2007	Width (MeV) PDG 2007	Number of Decays PDG		
			2002	2004	2007*
Spin Triplets					
$J/\psi$	3096.92±0.01	93.4±2.1 (keV)	134	135	162
$\psi(2S)$	3686.09±0.03	327±11 (keV)	51	62	115
$\chi_{c0}$	3414.75±0.35	10.4±0.7	17	17	51
$\chi_{c1}$	3510.66±0.07	0.89±0.05	12	13	35
$\chi_{c2}$	3556.20±0.09	2.05±0.12	18	19	37
Spin Singlets					
$\eta_c(1S)$	2979.8±1.2	26.5±3.5	20	21	31
$\eta_c(2S)$	3637±4	14±7	3	4	4
$h_c$	3525.93±0.27	<1	3	3	4

It is obvious from Table I that the parameters of *spin-triplet* states are measured with precision, and the number of measured decay channels is large (notice the marked improvements after 2004). This is not valid for *spin-singlet* states. A lot remains to be done for precision measurements of their parameters and decay channels.

Some new and recent experimental developments on charmonium spectroscopy below open flavor threshold will be reviewed.

## 2. Observation of $\eta_c(2S)$

It is important to identify the spin-singlet states in order to determine the hyperfine, or *spin-spin* interaction, which is responsible for singlet-triplet splitting of  $q\bar{q}$  states. Identification of  $\eta_c(2S)$  is important to know the possible variation of spin-spin interaction from Coulombic ( $J/\psi$ ,  $\eta_c(1S)$ ) to Confinement ( $\psi(2S)$ ,  $\eta_c(2S)$ ) regions of the  $q\bar{q}$  interaction. Most potential model calculations predicted  $M(\eta_c(2S)) = 3594\text{--}3626$  (MeV).

Prior to 2002 there were several unsuccessful attempts to identify  $\eta_c(2S)$  in  $p\bar{p}$ ,  $\gamma\gamma$ -fusion, inclusive photon analysis.

Finally,  $\eta_c(2S)$  was first observed in  $B$  decays by Belle [1]. It was followed by its observation in  $\gamma\gamma$ -fusion by CLEO [2] (see Fig. 2 left), and BaBar [3].

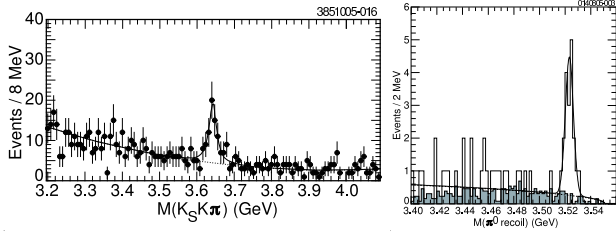


Figure 2: (left)  $M(K_s K \pi)$  from CLEO showing  $\eta_c(2S)$ . (right)  $\pi^0$  recoil mass spectrum from CLEO showing  $h_c$  in exclusive analysis of  $\psi(2S) \rightarrow \pi^0 h_c$ ,  $h_c \rightarrow \gamma \eta_c$ .

All available measurements of  $\eta_c(2S)$  are summarized in Table II. It is obvious that the spread in mass measurements is uncomfortably too large. The PDG 2007 weighted average value of mass is  $M(\eta_c(2S)) = 3637 \pm 4$  (MeV). This leads to the hyperfine splitting  $\Delta M_{hf}(2S) = 49 \pm 4$  (MeV). The hyperfine splitting value for  $1S$  states is  $\Delta M_{hf}(1S) = 117 \pm 1$  (MeV). Explaining large difference between  $\Delta M_{hf}(2S)$  and  $\Delta M_{hf}(1S)$  is a challenge for theorists. The width of  $\eta_c(2S)$  is essentially unmeasured (PDG 2007 value is  $\Gamma(\eta_c(2S)) = 14 \pm 7$  (MeV)). Measurement of the width is a challenge to the experimentalists. The decay of  $\eta_c(2S)$  is observed only in one decay channel,  $\eta_c(2S) \rightarrow K_s K \pi$ .

A lot remains to be done about  $\eta_c(2S)$ . Attempts are being made to identify  $\eta_c(2S)$  in the decay  $\psi(2S) \rightarrow \gamma \eta_c(2S)$  from 54  $pb^{-1}$  CLEOc  $\psi(2S)$  data. Thus, new results are expected from CLEOc.

Table II Measured parameters of  $\eta_c(2S)$  from different experiments (PDG 2007).

Exper.	$M(\eta_c(2S))$	$\Gamma(\eta_c(2S))$	Events(reaction)
Belle[1]	$4654 \pm 10$	$< 55$	$39 \pm 11$ ( $B \rightarrow K(K_s K \pi)$ )
CLEO[2]	$3643.9 \pm 3.4$	$6.3 \pm 13.0$	$61 \pm 15$ ( $\gamma\gamma \rightarrow K_s K \pi$ )
BaBar[3]	$3630.8 \pm 3.5$	$17.0 \pm 8.7$	$112 \pm 24$ ( $\gamma\gamma \rightarrow K_s K \pi$ )
BaBar[4]	$3645.0 \pm 8.4$	$22 \pm 14$	$121 \pm 27$ ( $e^+e^- \rightarrow J/\psi c\bar{c}$ )
Belle[5]	$3626 \pm 8$	-	$311 \pm 42$ ( $e^+e^- \rightarrow J/\psi c\bar{c}$ )

### 3. Observation of $h_c(1P_1)$

The observation and the measurement of the parameters of  $h_c$  is important to determine the hyperfine splitting of P-states  $\Delta M_{hf}(1P) \equiv M(<^3 P_J>) - M(1P_1)$ , which is expected to be zero from the lowest order pQCD calculations.

Recently CLEO Collaboration has unambiguously identified  $h_c$  in their data for 3 million  $\psi(2S)$  [6]. Data have been analyzed for the reaction  $\psi(2S) \rightarrow \pi^0 h_c$ ,  $h_c \rightarrow \gamma \eta_c$  in both inclusive and exclusive studies. In

inclusive analysis, photon energy or  $\eta_c$  mass (recoil against  $\pi^0 \gamma$ ) was constrained. In exclusive analysis seven known  $\eta_c$  decay channels with a total branching fraction of  $\sim 10\%$  were measured. Results of inclusive and exclusive analysis are consistent. The final plot of the  $\pi^0$  recoil spectrum from exclusive analysis is shown in Fig. 2 (right).

The overall results are:

$$\begin{aligned}
 M(h_c) &= (3524.4 \pm 0.6 \pm 0.4) \text{ MeV}; \\
 \Delta M_{hf}(1P) &= (+1.0 \pm 0.6 \pm 0.4) \text{ MeV}, \\
 \text{using } M(<^3 P_J>) &= (3525.4 \pm 0.1) \text{ MeV}; \\
 Br(\psi(2S) \rightarrow \pi^0 h_c) \times Br(h_c \rightarrow \gamma \eta_c) &= (4.0 \pm 0.8 \pm 0.7) \times 10^{-4};
 \end{aligned}$$

Significance level of the  $h_c$  signal is  $> 6\sigma$ .

The conclusions are that a) the lowest order pQCD expectation  $\Delta_{hf}(1P) = 0$  is not strongly violated, and b) the magnitude and the sign of  $\Delta_{hf}(1P)$  is not well determined.

The Fermilab E835  $p\bar{p}$  annihilation experiment has also claimed  $h_c$  observation at  $\sim 3\sigma$  level in the reaction  $p\bar{p} \rightarrow h_c \rightarrow \gamma \eta_c$  and reported  $\Delta_{hf}(1P) = -0.4 \pm 0.2 \pm 0.2$  (MeV) [7].

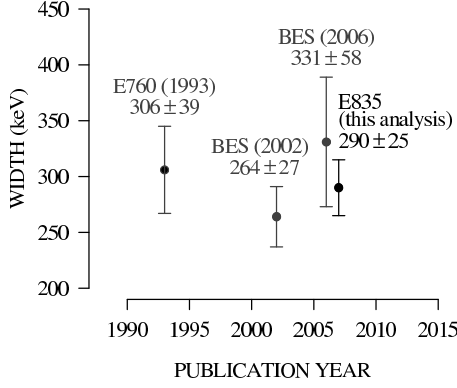
CLEOc now has new data with 24 million  $\psi(2S)$  events, and a  $h_c$  peaks with  $\sim 250$  and  $\sim 1000$  counts are expected in exclusive and inclusive analysis respectively, which will reduce the error on mass measurement more than a factor of two.

### 4. Measurements of the $\psi(2S)$ Widths

Using  $p\bar{p}$  annihilation to form charmonium  $c\bar{c}$  states, Fermilab experiment E835 achieved unprecedented precision in measuring masses and widths of charmonium resonances. This happens due to taking advantage of stochastically cooled antiproton beams, with FWHM energy spreads of 0.4-0.5 MeV in the center-of-mass frame.

Recently new precision measurement of the  $\psi(2S)$  total width was performed from excitation curves obtained in  $p\bar{p}$  annihilations from 1.64  $pb^{-1}$  scan data in the  $\psi(2S)$  region, collected by E835 in 2000 [8]. The channels analyzed were  $p\bar{p} \rightarrow e^+e^-$  and  $p\bar{p} \rightarrow J/\psi X \rightarrow e^+e^- + X$ . New technique of “complementary scans”, based on precise beam revolution-frequency and orbit-length measurements was used. Resonance parameters were extracted from a maximum-likelihood fit to the excitation curves. The total width of the  $\psi(2S)$  and the combination of partial widths were measured:  $\Gamma_{tot}(\psi(2S)) = (290 \pm 25 \pm 4) \text{ keV}$ ,  $\Gamma_{e^+e^-} - \Gamma_{p\bar{p}} / \Gamma_{tot} = 579 \pm 38 \pm 36 \text{ meV}$ . These represent the most precise measurements to date (Fig. 3).

BES has also measured recently the  $\psi(2S)$  total width using  $e^+e^-$  annihilation scan data in the  $\psi(2S)$  and  $\psi(3770)$  regions, collected by BES II in 2003 [9] (Fig. 3). They have analyzed the channel  $e^+e^- \rightarrow$


 Figure 3: Recent measurements of the  $\psi(2S)$  widths.

*hadrons*. Resonance parameters were extracted from simultaneous fit of cross section curves covering energy ranges of both  $\psi(2S)$  and  $\psi(3770)$  resonances:

$$\Gamma_{tot}(\psi(2S)) = (331 \pm 58 \pm 2) \text{ keV},$$

$$\Gamma_{ee}(\psi(2S)) = (2.330 \pm 0.036 \pm 0.110) \text{ keV}.$$

## 5. Measurements of the $J/\psi$ Widths

Using  $281 \text{ pb}^{-1}$  CLEOc  $\psi(3770)$  data and looking for radiative return events to  $J/\psi$ , CLEO has measured the widths of the  $J/\psi$  [10]. They selected  $\mu^+\mu^-(\gamma)$  events, each with a dimuon mass in the region of the  $J/\psi$ , and counted the excess over non-resonant QED production. Resulting cross section is proportional to  $Br_{\mu\mu} \times \Gamma_{ee}(J/\psi)$ . Assuming lepton universality and dividing by CLEO's own measurement of  $Br_{ll} = (5.953 \pm 0.056 \pm 0.042)$  [11], they obtained  $\Gamma_{ee}(J/\psi)$ . Dividing once more by  $Br_{ll}$  they obtained  $\Gamma_{tot}(J/\psi)$ :

$$Br_{\mu\mu} \times \Gamma_{ee}(J/\psi) = (0.3384 \pm 0.0058 \pm 0.0071) \text{ keV};$$

$$\Gamma_{ee}(J/\psi) = (5.68 \pm 0.11 \pm 0.13) \text{ keV};$$

$$\Gamma_{tot}(J/\psi) = (95.5 \pm 2.4 \pm 2.4) \text{ keV}.$$

These represent the most precise measurements to date.

## 6. Measurements of the $\eta_c(1S)$ and $\chi_{c0,c2}(1P)$ Parameters in Two-Photon Fusion Reaction

The masses and widths of the spin-triplet  $\chi_{cJ}(1P)$  states are measured with high precision at Fermilab  $p\bar{p}$  experiments E760/E835. But the mass and width of the spin-singlet  $\eta_c(1S)$  state are known with only  $\sim 1 \text{ MeV}$  and  $\sim 3 \text{ MeV}$  precision respectively.

Using  $395 \text{ fb}^{-1}$  data sample accumulated with the Belle detector, measurements of the  $\eta_c(1S)$  and  $\chi_{c0,c2}(1P)$ , produced in two-photon collisions and de-

caying to four-meson final states ( $4\pi$ ,  $2K2\pi$ ,  $4K$ ) were performed [12] (Fig. 4).

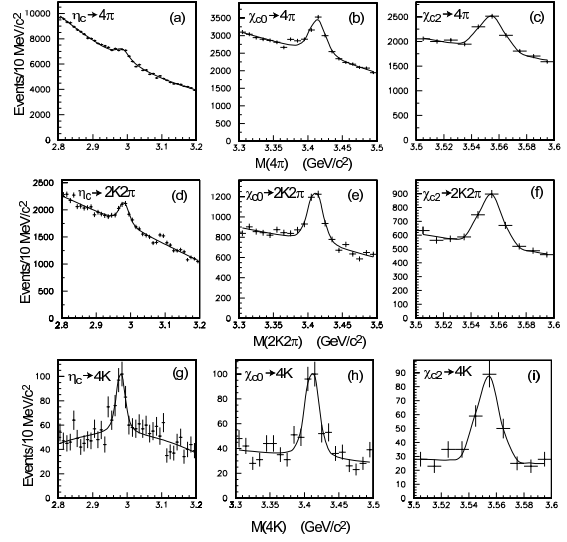


Figure 4: Results of the fits to the invariant mass distributions.

### 6.1. Mass and width of the $\eta_c(1S)$ and $\chi_{c0,c2}(1P)$

The measured values of the mass and width of  $\eta_c(1S)$  and  $\chi_{c0,c2}(1P)$ , and the number of signal events used in analysis are presented in Table III. The values of the mass and width for  $\chi_{c0}(1P)$  and  $\chi_{c2}(1P)$  are consistent within errors with the previous high precision measurements. The precision of the measured mass and width of  $\eta_c(1S)$  is comparable to other available precision measurements.

 Table III Mass and width measurements of the  $\eta_c(1S)$ ,  $\chi_{c0}(1P)$  and  $\chi_{c2}(1P)$  from [12].

Resonance	Mass (MeV)	Width (MeV)	N(events)
$\eta_c(1S)$	$2986.1 \pm 1.0 \pm 2.5$	$28.1 \pm 3.2 \pm 2.2$	$7616 \pm 553$
$\chi_{c0}(1P)$	$3414.2 \pm 0.5 \pm 2.3$	$10.6 \pm 1.9 \pm 2.6$	$5459 \pm 319$
$\chi_{c2}(1P)$	$3555.3 \pm 0.6 \pm 2.2$	-	$2503 \pm 158$

### 6.2. Two-photon widths of $\eta_c(1S)$ and $\chi_{c0,c2}(1P)$

The two photon decay of the positive C-parity charmonium states in the lowest order is a pure QED process. The measurements of the two photon partial widths of these states can shed light on higher order relativistic and QCD radiative corrections.

The values of the two photon partial widths of  $\eta_c(1S)$  and  $\chi_{c0,c2}(1P)$ , evaluated from the measurements of the  $\Gamma_{\gamma\gamma} \times Br$  by Belle [12], are presented in Table IV. They are compared to the values obtained from the PDG 2007. The Belle value of  $\Gamma_{\gamma\gamma}(\eta_c)$  is  $\sim 2.7$  times smaller ( $\sim 4\sigma$  difference) than the PDG 2007 value. The values of  $\Gamma_{\gamma\gamma}(\chi_{c0})$  and  $\Gamma_{\gamma\gamma}(\chi_{c2})$  are consistent within errors with those from the PDG 2007.

The ratio  $R \equiv \Gamma_{\gamma\gamma}(\chi_{c2})/\Gamma_{\gamma\gamma}(\chi_{c0})$  is an interesting quantity, because it allows us to evaluate the reliability of the first order radiative corrections, which are often very large, by calculating  $\alpha_s$  from them

$$R \equiv \frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{\gamma\gamma}(\chi_{c0})} = \frac{(4|\Psi'(0)|^2 \alpha_{em}^2/m_c^4) \times (1-1.7\alpha_s)}{(15|\Psi'(0)|^2 \alpha_{em}^2/m_c^4) \times (1+0.06\alpha_s)} = 0.267(1-1.76\alpha_s)$$

The Belle value  $R=0.221 \pm 0.041$  leads to  $\alpha_s=0.098 \pm 0.085$ , which is obviously underestimate of  $\alpha_s(m_c)$ , which is known to be  $\sim 0.3$ . This makes questionable the reliability of nearly 50% first order correction factor for  $\Gamma_{\gamma\gamma}(\chi_{c2})$ .

Table IV Two photon partial widths  $\Gamma_{\gamma\gamma}$  of  $\eta_c(1S)$ ,  $\chi_{c0}(1P)$  and  $\chi_{c2}(1P)$  [12].  $\Gamma_{\gamma\gamma}$  values are evaluated from measured  $\Gamma_{\gamma\gamma} \times Br$  using branching fractions from PDG 2007. Results of  $4\pi$ ,  $2K2\pi$  and  $4K$  channels are combined.

Resonance	$\Gamma_{\gamma\gamma}$ (keV), Belle	$\Gamma_{\gamma\gamma}$ (keV), PDG 07
$\eta_c(1S)$	$2.46 \pm 0.60$	$6.7 \pm 0.9$
$\chi_{c0}(1P)$	$1.98 \pm 0.24$	$2.90 \pm 0.43$
$\chi_{c2}(1P)$	$0.438 \pm 0.062$	$0.539 \pm 0.050$
$R \equiv \Gamma_{\gamma\gamma}(\chi_{c2})/\Gamma_{\gamma\gamma}(\chi_{c0})$	$0.221 \pm 0.041$	$0.186 \pm 0.032$

## 7. Summary

All Charmonium states below open flavor threshold have now been firmly identified.

The spectroscopy of spin-triplet states is now well in hand, but a lot still needs to be done for spin-singlet states. Masses, widths, particularly of  $\eta_c(2S)$

and  $h_c(1^1P_1)$  need to be better determined. Many more decay channels need to be investigated for each.

A large number of investigations, based on the world's largest sample of  $\psi(2S)$  acquired by CLEOc, are currently in progress, and results are expected soon. These include:

- Precision results for mass, width and branching fractions of  $h_c(1^1P_1)$ ;
- Results for many decay channels of  $\eta_c(1S)$ ;
- Results for attempt to identify  $\eta_c(2S)$  in radiative decay of  $\psi(2S)$ ;
- Results of studies for  $p\bar{p}$  threshold enhancement in radiative decays of  $J/\psi$ ,  $\psi(2S)$ ;
- Results of search for tensor glueball,  $\xi(2230)$ ;
- Hadronic and radiative decays of  $\psi(2S)$  and  $J/\psi$ ;
- Two-body and multi-body decays of  $\chi_{cJ}(1P)$  states, and others.

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